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ON EXPLORING THE POWER QUALITY ENHANCEMENT CAPABILITY AND OTHER ANCILLARY FUNCTIONALITIES OF SOLID STATE TRANSFORMER APPLICATION IN THE DISTRIBUTION SYSTEM

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ABSTRACT

Nowadays, the distribution grids are facing technical challenges due to the increased connection of sizeable loads like electric vehicle (EV) charging stations as well as large penetration of distributed renewable energy resources (DRERs) notably wind energy conversion system (WECS) and solar power plant (SPP), thus resulting in some operational issues in the form of power quality disturbance, reliability issues and grid congestion. To this extent, solid state transformer (SST) has been envisioned as a promising device for improving the power quality, providing a bidirectional power flow capability as well as ensuring a smooth and safe way of interfacing DRERs with the distribution grid. This paper reviews the basic power quality parameters in electrical power system, the role of SST in power quality improvement as well as some other ancillary services that SST can offer to the grid which cannot be achieved with the conventional line frequency transformer (LFT).

Keywords: Solid state transformer (SST); distribution grid; power quality; reactive power; harmonics.

1. INTRODUCTION

A portable, smart and intelligent power electronic device is required to support the ever increased connection of sizeable loads like electric vehicle (EV) charging stations and distributed renewable energy resources (DRERs) typically in the form of wind energy conversion system (WECS) and solar power plant (SPP) to the distribution grids. In this regard, researchers have been motivated to consider replacing the conventional line frequency transformer (LFT) with a power electronic transformer (PET) capable of maintaining the reliability of the distribution grids especially during transients. The PET commonly referred to as solid state transformer (SST) is an emerging technology designed with improved intelligence, sensing and control capabilities. In particular, SST guarantees full-range control of both terminal voltage and current, thereby providing room for reactive power regulation (Huber & Kolar, 2019).

In order to support the distribution grid to cater to transients and other contingencies arising from connection of EVs and DRERs, the SST has been investigated by many researchers and found to be capable of not only replacing the LFT in providing voltage transformation, but also in providing other ancillary functionalities (Londero, Mello, & Silva, 2019a). The power electronic stages of the SST allows self-control of terminal voltages and currents, thus making it easier to regulate the flow of active and reactive power. This capability allows the device to cater for power quality issues such as voltage sag, voltage swell, voltage flicker, voltage transients and harmonics. Other functionalities of SST has also being investigated regarding but not limited to distribution grid. For example, researchers in (Kadandani, Dahidah, & Ethni, 2021a) have investigated the use of SST in WECS where it was established that the SST can effectively be used to provide a smooth integration of wind farm with the grid. In a similar development, researchers in (Foureaux, Adolpho, Silva, Brito, & Filho, 2014) have investigated the application of SST in utility scale solar power plants. SST has also been considered for smart grid application as reported in (Kadandani, Dahidah, & Ethni, 2021b). An in-depth study of the application of SST in design of high-power electric vehicle charging stations was presented in (Eshkevari, Mosallanejad, & Sepasian, 2020). Furthermore, the SST has also been investigated for use in flexible AC transmission system (FACTS) as demonstrated in (Shah & Crow, 2016). In a similar development, the power management strategy for DC microgrid interfaced to distribution system based on SST has been investigated in (Yu, She, Ni, Wang, & Huang, 2013).

The intent of this paper is to explore the power quality enhancement capability and other ancillary functionalities of SST in distribution grids. The remaining part of the paper is organized as follows. Section 2 presents the basic concept of SST. Section 3 presents some common power quality parameters in electrical system. In section 4, the role of SST in power quality improvement is presented. Section 5 entails the other ancillary functionalities of SST. Finally, section 6 concludes the paper.

2. THE CONCEPT OF SOLID STATE TRANSFORMER (SST)

2.1. SST Configurations and Topologies

As shown in Figure 1, the concept of SST comprises of power electronic converters designed to interphase high (or medium) voltage and low voltage with the aid of high frequency transformer (HFT) thereby providing galvanic isolation between the two voltage levels (Kadandani, Dahidah, Ethni, & Yu, 2019). Thus, the SST changes the 50/60Hz medium (or high) AC voltage to a high frequency one which is further stepped up or down using HFT and finally shaped back to the desired 50/60Hz AC voltage (Huang, 2016). The SST is not just a replacement to LFT, but offers other benefits of being portable with reduced size, free from greenhouse emission and equipped with intelligence for bidirectional power flow capability, fault ride through capability, reactive power support to the grid and power quality improvement.

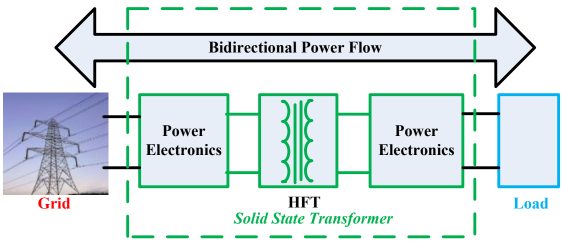

Figure 1: Block diagram of solid state transformer

SST system combines both power electronics conversion and HFT electrical energy conversion techniques for the controlling and managing electrical power so as to enhance flexible regulation capability of the distribution grid (Sun, Li, Ma, Zhang, & Qin, 2021). As shown in Figure 2, the concept of SST can be realized in three basic topologies, namely; *single stage topology* with AC semiconductor switches on both input and output connected with HFT, *two stage topology* with an AC/DC converter followed by an inverter and *three stage topology* based on AC/DC – DC/DC (including isolation) – DC/AC converters in cascaded passion (H. Chen & Divan, 2018). The latter topology comprises of medium voltage AC/DC converter, low voltage DC/DC converter, medium frequency converter and a high frequency converter and commonly used for power quality improvement and providing other ancillary services to the distribution grid.

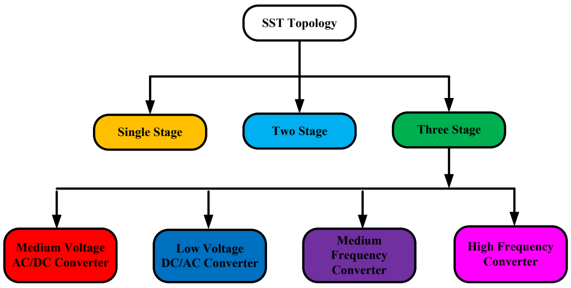

Figure 2: SST topology classification

SST is being considered as an emerging technology that can replace the bulky LFT in voltage transformation with additional ancillary services to the grid such as reactive power compensation / harmonic filtering, disturbance and fault isolation and many more. When used in the grid integration of DRERs like wind farms, the SST can provide a direct substitute for static synchronous compensator (STATCOM), its coupling transformer, the bulky step-up LFT and active power filter (APF). In fact, SST can be used for power quality improvement in grid connected wind farms faster than the conventional FACTS devices. In traction and other locomotives, SST is also being considered as a direct substitute of LFT for decreased space and volume.

2.2. Selection of Suitable SST Configuration

Requirements of the SST for the Research Study:

- For this research, we need a configuration where it is possible to add distributed energy sources (DES) and distributed energy storage devices (DESD)
- A topology that provide services such as reactive power and voltage sag compensation, integration of DRERs and DESDs, and bidirectional power flow
- A topology that enables dc-link connectivity and also guarantees input/ output decoupling of voltages and currents, providing the system control more degrees of freedom
- A configuration in which voltage or current can be separately controlled in each stage. .
- A topology with high voltage DC (HVDC) and low voltage (LVDC) links to enhance the ride-through capability of the SST and allow power quality improvement in the input and in the output.

Proposed Choice for the Research Study:

- The most feasible configuration of the SST satisfying the above requirements is the three-stage configuration (Figure 3) i.e. topologies with both HVDC and LVDC-links available.
- To handle the HV level involved on the power conversion, modular architectures bring several advantages, such as low electromagnetic interference emission, the potential to use standard LV-rating devices, and modularity, which allows for the implementation of redundant strategies to increase fault tolerance and availability. For these reasons, modular architectures are preferable for SST applications.
- Multilevel converter topologies can be implemented in each stage and optimize the SST for high voltage or high-power applications.

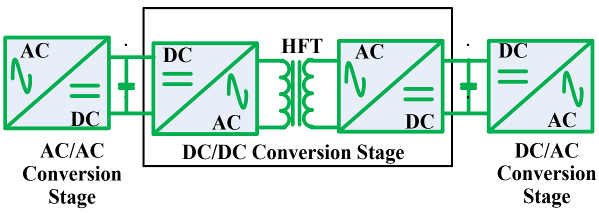

Figure 3: Three stage SST Configuration for the research study

Advantages for the Chosen 3-Stage Configuration:

✓ The DC links enable independent reactive power control and input voltage sag ride through capability by decoupling the HV from the LV

- ✓ Its LVDC support the integration of distributed energy storage devices and renewable energy sources while the HVDC supports high voltage operation
- ✓ It possess good output voltage and input current regulation
- ✓ It provides input and output current limiting capability
- ✓ It has independent frequency and independent power factor
- ✓ It has a very simple modularity implementation
- ✓ The DC/DC conversion stage enables galvanic isolation and voltage adaptation.
- ✓ The presence of two different voltage level DC links allows interconnecting the energy storage devices and renewable energy sources into one system without additional converters.
- ✓ High flexibility and control performance

The input AC/DC conversion stage of the three stage topology is responsible for absorbing active power from the source (AC grid) and feed it to the next stage. The other task for this unit is the control of reactive power for grid services (Liserre et al., 2016). The DC/DC conversion stage is required to provide galvanic isolation between the high voltage side and the low voltage side. In this stage, the low frequency high voltage input AC signal of the SST is transformed into low voltage high frequency. (Liserre et al., 2016). Unlike the other two conversion stages, the output DC/DC conversion stage which is located on the low voltage side and it is required to supply high current. This last conversion stage is the most exposed to the disturbances on the load side.

3. COMMON POWER QUALITY PARAMETERS IN ELECTRICAL SYSTEM

The term *power quality* refers to the ability of an electrical system to give a perfect power supply that is of smooth sinusoidal waveform with stable voltage and frequency and free from any noise (Hossain, Tür, Padmanaban, Ay, & Khan, 2018). In an ideal situation, the voltage and current waveforms of an electrical power system network are of smooth sinusoidal shape and free from any kind of distortions. A three phase power network for example has its current and voltage waveforms being in phase and the phase voltages (or currents) are of equal magnitude and displaced by 120^o from each other as depicted in Figure 4. Power quality issue arises whenever there is any deviation in the smooth nature of the voltage or current waveform as a result of equipment malfunction or connection of sizeable and nonlinear loads (Kadandani, 2015).

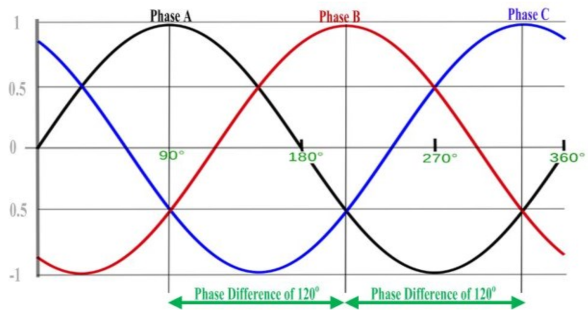

Figure 4: An ideal 3-phase system

Power quality is directly related to the behavior of the electrical power system network in terms of technical performance and reliability of the power system network (Earnest & Wizelius, 2011). The technical performance are measured in terms of transient stability, voltage quality, absence of harmonics, and frequency stability among others. In the case of power system reliability, the system is be highly available without interruptions.

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3.1. Voltage Sag

Voltage sag is said to occur when a power system experiences a sudden reduction in the rms value of its voltage magnitude between 10% and 90% for a duration of half cycle to one minute as illustrated in Figure 5.

Voltage sag usually originates from grid short circuit, start-up of large DRERs (such as high capacity wind turbines) and start-up of large motor drives. The main impact of voltage sag include fail functions of equipment and disconnection of sensitive loads.

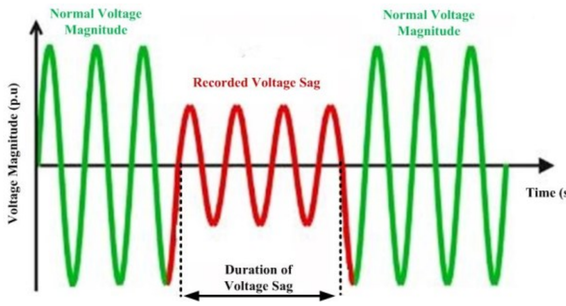

Figure 5: Illustration of voltage sag

3.2. Voltage Swell

Voltage swell is the increase in the rms value of the voltage from 110% to 180% for a duration of half cycle to one minute as illustrated in Figure 6.

Voltage swell may occur as a result of grid lightning strikes, shutdown of large capacity DRERs, earth fault on another phase or when there is wrong setting in substation. Voltage swell can leads to aging of insulation, disconnection of equipment and at times can harm equipment with inadequate design margins.

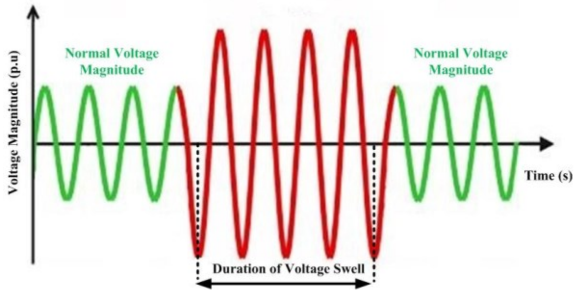

Figure 6: Illustration of voltage swell

3.3. Voltage Flicker

Flicker is a kind of voltage fluctuation experienced by light bulbs and being physically observed by human eye as depicted in Figure 7. Flicker can be caused by industrial motors, X-ray machines, arc welders, saw mills, electric boilers, etc. In the case of grid with large penetration of DRERs (say wind power plant for example), flicker can originates from turbulence intensity, wind turbine yaw error, wind shear, wind turbine blade pitch error, wind turbine shadow effect and changes in the wind speed. Flicker can results in fail function of equipment, aging of insulation as well as flickering of lamps.

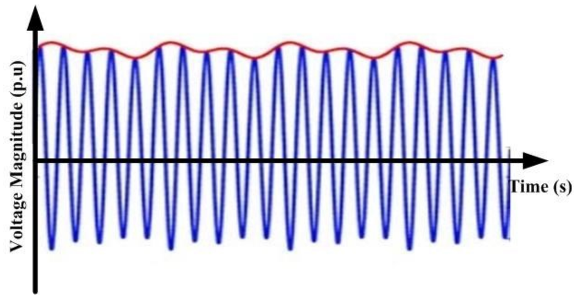

Figure 7: Illustration of voltage flicker

3.4. Voltage Transient

Voltage transients are typically caused by lightning resulting in sudden and significant deviation of the waveforms from normal levels. Transients usually last for a very short duration (milli or microseconds). Power quality disturbance due to voltage transients typically originates from lightning strike as well as switching events of large loads and generators in high capacity wind power plants.

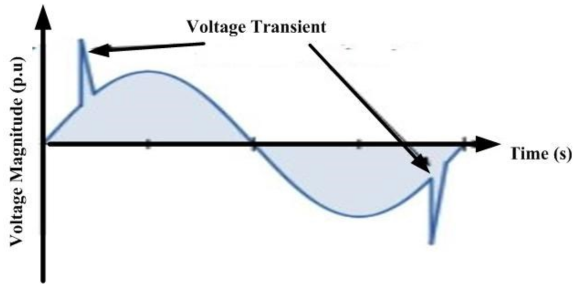

Figure 8: Illustration of voltage transient

3.5. Undervoltage

Undervoltage is said to occur when the rms value of the voltage falls below 90% of its nominal value for a duration of more than 60 seconds. The phenomena of undervoltage is illustrated in Figure 9.

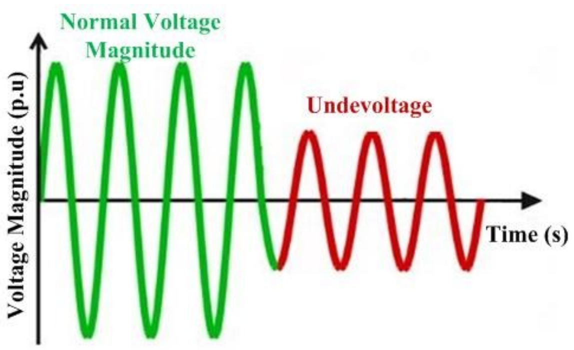

Figure 9: Illustration of undervoltage

3.6. Overvoltage

Overvoltage refers to the situation when the rms voltage value rises above 110% of its nominal value for a duration of more than 60 seconds as shown in Figure 10.

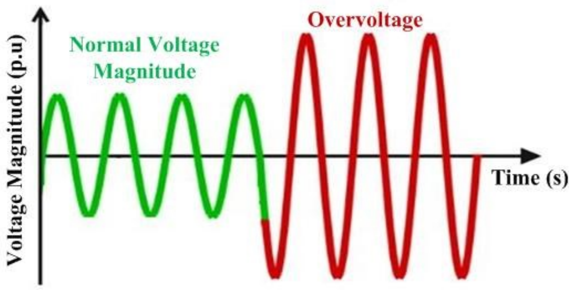

Figure 10: Illustration of overvoltage

3.7. Harmonic Distortions

Harmonic distortions are said to occur whenever frequencies of multiple integers of the fundamental frequency are added to the voltage or current waveform, thus resulting into periodic deviation from the original waveform as shown in Figure 11.

Power quality disturbances due to harmonic distortions usually originates from connection of non-liner loads, transformer saturation, and resonance phenomena. The main impacts of harmonic distortion are extended heating and failure of electronic equipment.

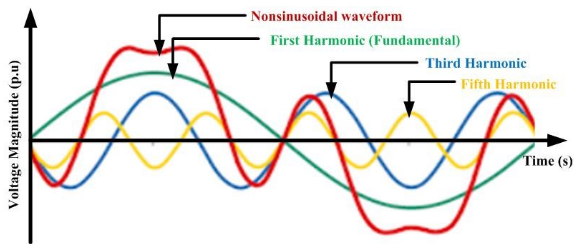

Figure 11: Illustration of harmonics

3.8. Voltage Interruptions

Voltage interruptions represents a situation when there is complete loss of voltage on one or more phases for a certain duration of time as shown in Figure 12. Depending on the time duration, interruption can be classified into short and long interruptions. The sooner stays for few milliseconds to two seconds while the latter usually exceeds two seconds.

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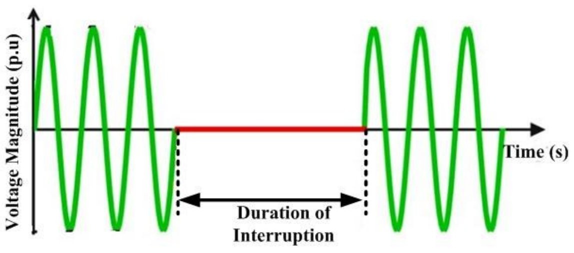

Figure 12: Illustration of voltage interruptions

4. ROLE OF SST IN POWER QUALITY IMPROVEMENT

As shown in Figure 13, SST is configured to allow the flow of active and reactive power, as such can be used to provide control of terminal voltage and current. The SST can regulate the low voltage buses, thus leading to the control of active and reactive power and or frequency/power control for the grid side port. The voltage control is achieved by delivering or absorbing reactive power. The SST can also filter harmonics components and provide reactive power support. This can be achieved easily if a voltage source converter (VSC) is employed on the high voltage side of the SST (She & Huang, 2013). The SST configuration of Figure 12 can regulate any voltage fluctuation that are caused by transients and other power quality disturbances without additional reactive power compensation devices like STATCOM.

The reactive power control on the HV side of the SST is achieved by volt/var control, in which case, a step of increase or decrease in the reactive power is defined such that (Londero, Mello, & Silva, 2019b):

$$Q_{SST} = Q_{SST} \pm \Delta Q \qquad (1)$$

where

Q_{SST} is the reactive power of the SST, and

ΔQ is the fixed step.

Based on (1), the control architecture will increase the SST reactive power whenever the system reactive power is negative. Conversely, the control technique will decrease the SST reactive power when that of the system is positive. In the same passion, when the system voltage drops beyond its lower limit, the control architecture will reduce the SST reactive power to allow it inject the reactive power to the system thereby raising its voltage profile. Conversely, when the system voltage rises beyond its upper limit, the control architecture will increase the SST reactive power to allow it absorb the reactive power to the system thereby lowering its voltage profile.

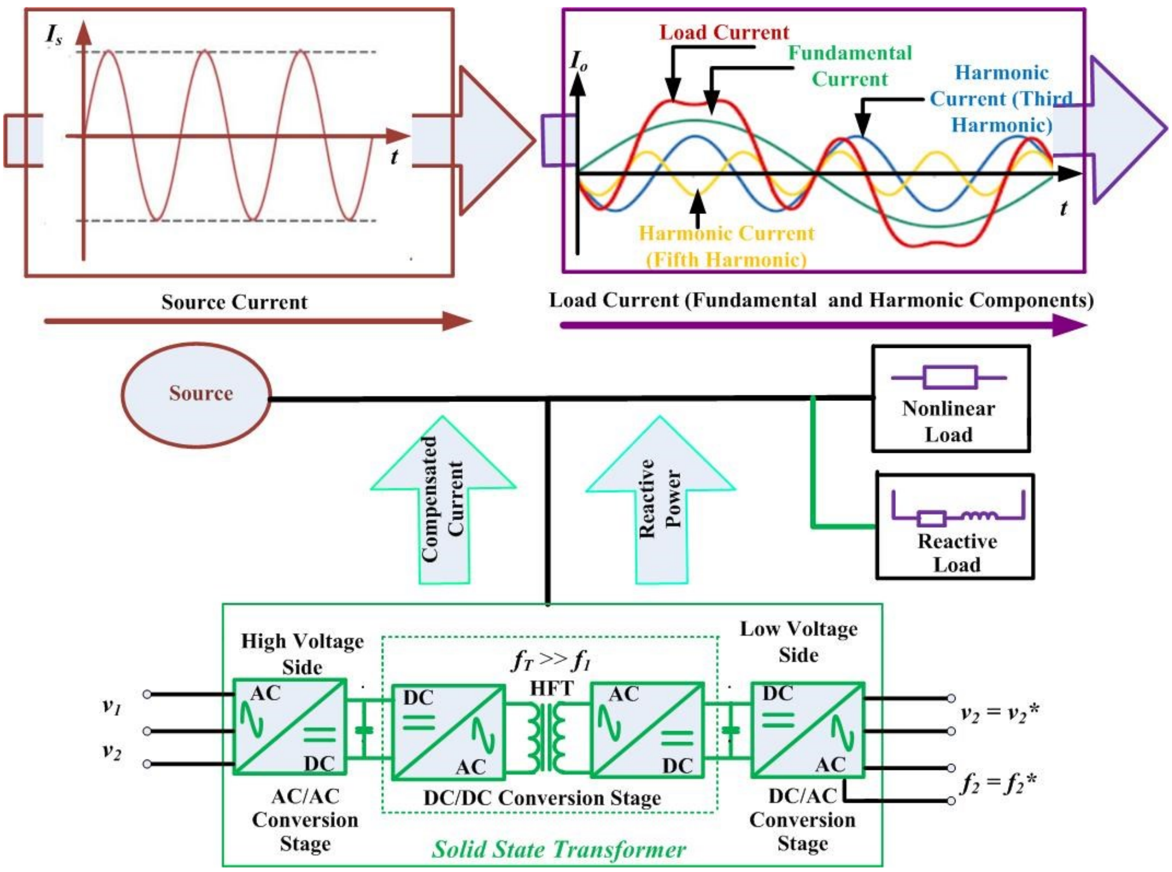

Figure 13: Illustration of the role of SST in power quality improvement

5. OTHER ANCILLARY FUNCTIONALITIES OF SST IN DISTRIBUTION GRIDS

5.1. SST in Wind Energy Conversion System

The three approaches reported in the literature for the conversion of wind energy into electrical energy are squirrel-cage induction generator (SCIG) based WECS, doubly-fed induction generator (DFIG) based WECS, and directly driven synchronous generator (DDSG) based WECS (She, Wang, Burgos, & Huang, 2012). As shown in Figure 14, modern WECS uses SST as a substitute for LFTs, static synchronous compensator (STATCOM) and capacitor banks required for power factor correction thereby saving space and volume, Thus, the SST-based WECS gives compactness and high performance. The SST provides direct interface to the grid while realizing the task of isolation and voltage adaptation. It can effectively suppress the voltage fluctuation caused by the transient nature of wind energy without additional reactive power compensator and, as such, may enable large penetration of wind power into the power grid (She, Huang, Wang, & Burgos, 2013).

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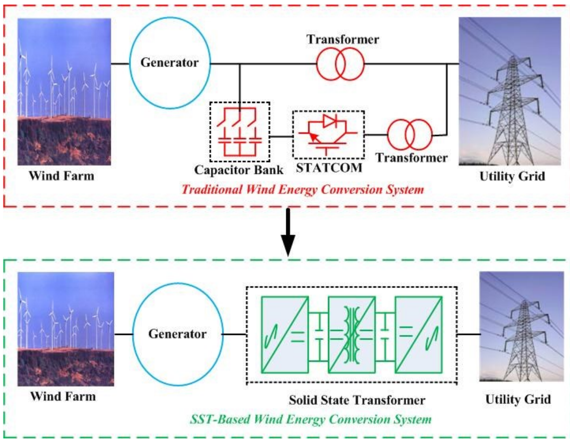

Figure 14: Role of SST in wind energy conversion system

5.2. SST in Solar Power Plant

SST has also been considered for the grid connection of photovoltaic inverters as demonstrated in (Liu, Zha, Zhang, & Chen, 2016). In fact, a compact and reliable solar power plant can be realized if a multilevel converter based SST is used in the illustration shown in Figure 15.

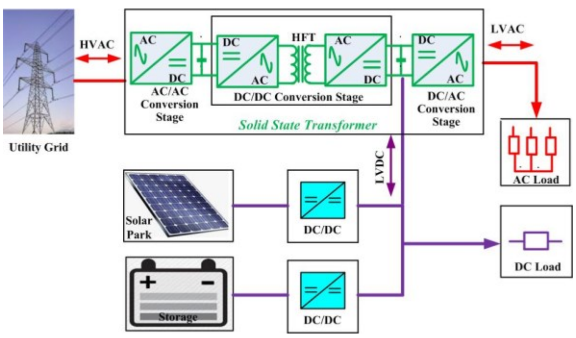

Figure 15: Illustration of the role of SST in solar power plant

5.3. SST in Electric Vehicle DC Fast Charging System

When integrated to the EV charging station, the SST provides a common DC link to adapt to the EV. As shown in Figure 16, a portable SST with reduced space and volume is used in EV DC fast charging station and it allows better control of the charging process than the traditional method (Q. Chen, Liu, Hu, Wang, & Zhang, 2017).

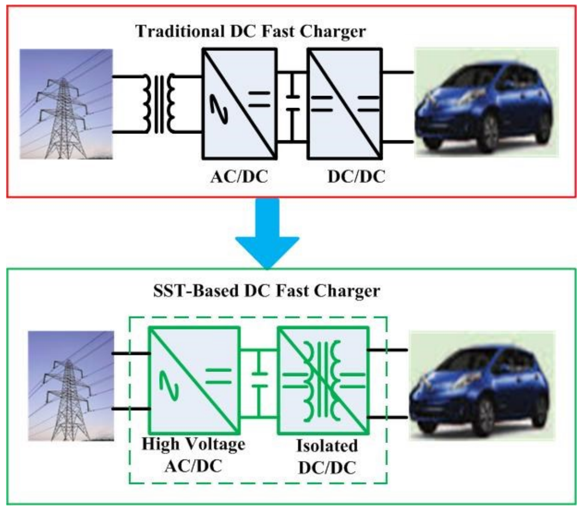

Figure 16: SST used in DC fast charging station

5.4. SST in Smart Grid

The control flexibility and other multiple functionalities of SST makes it a suitable aiding device in smart grid applications. Figure 17 illustrates the role of SST in smart grid. As can be seen, the SST with its intelligence and sensing capabilities ensures proper management of the source and load sides of the system such that the distribution of energy in the distribution grid is dynamically balanced.

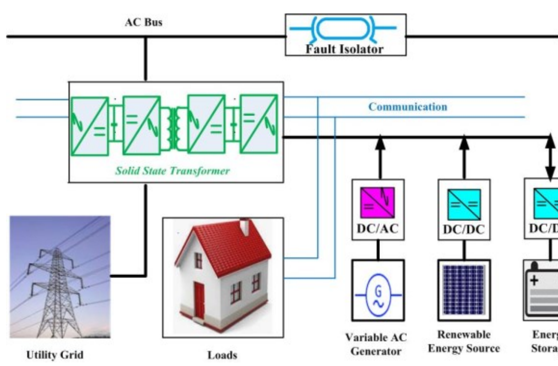

Figure 17: SST used in smart grid

5.5. SST in Traction System

Modern traction system is one sector where space and volume are critical, thus motivating the use of portable SST against the traditional LFT. Figure 18 shows an SST-based traction system where the SST ensures flexibility of the system, reduce harmonic distortion and improves the system efficiency.

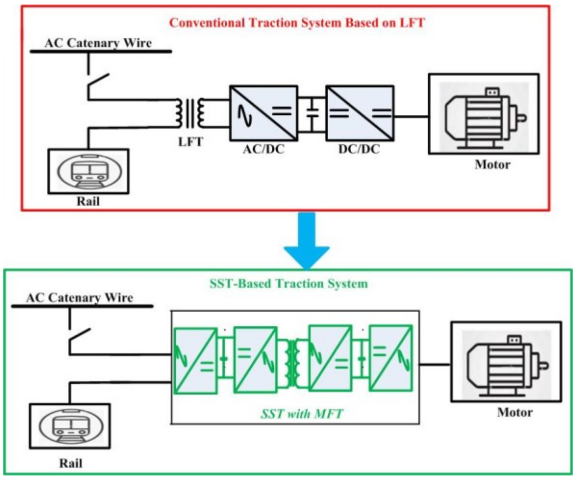

Figure 18: SST used in traction system

5.6. SST in Microgrid

The concept of microgrid was motivated by the ever daily advancement and further development of DRERs such as solar PVs and WECS. The microgrid enhances the smooth integration of DRERs to the distribution grid with the aid of SST. In the configuration shown in Figure 19, the SST ensures fault limitation and isolation, reactive power support, harmonic mitigation and power quality improvement.

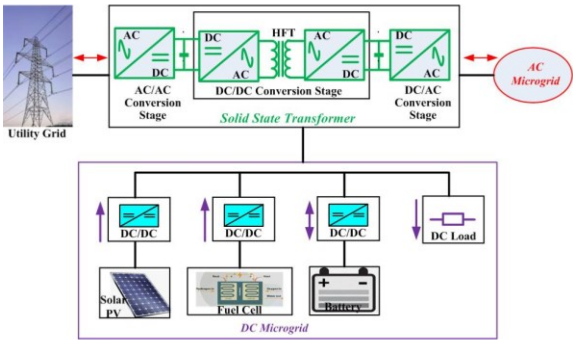

Figure 19: Illustration of the role of SST in modern microgrid

5.7. SST in Flexible AC Transmission System

Flexible AC transmission system (FACTS) devices are usually incorporated in an electrical network to provide reactive power compensation and are typically connected in series, shunt or series-shunt (Kadandani & Maiwada, 2015). However, FACTs devices are heavy and bulky; hindering them from application where space is of great concern. This gives a room for consideration of SST as substitute for the FACTS controllers. In the configuration shown in Figure 20, a portable SST is used in place of FACTS device and it is capable of controlling both real and reactive power apart from minimizing the size and weight of the system.

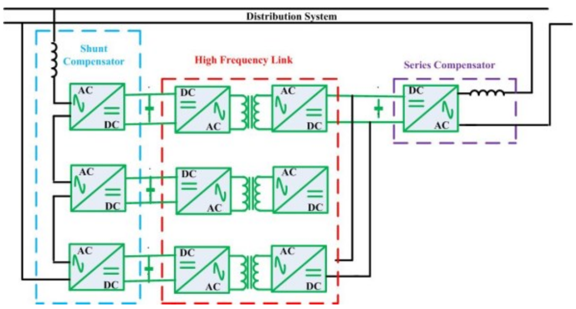

Figure 20: Illustration of the role of SST in FACTS

6. CONCLUSION

The paper has explored how SST can be used to enhance power quality in the distribution grids. In this regard, it has been demonstrated in the paper that with the help of intelligence and flexibility of the SST, the modern distribution grids can withstand the ever increasing connection of sizeable loads like EV, and other sophisticated and non-linear load. It has also been established that with the SST, terminal voltage control, reactive power support, fault limitation and harmonic filtering can also be achieved. Further, the paper has explored other ancillary services that SST can offer to the distribution grid which are not achievable with the conventional LFT. Thus, it has been established in the paper that when applied in the distribution system, the SST can mitigate the problems introduced by DRERs and improve the power quality as well as the flexible regulation capability of the distribution grids.

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